CS - 3

STUDY OF HYDROMETEOROLOGICAL ASPECTS OF NARMADA BASIN

S RAMASESHAN
DIRECTOR

STUDY GROUP

S M SETH

K S RAMASASTRI

NATIONAL INSTITUTE OF HYDROLOGY

JAL VIGYAN BHAVAN

ROORKEE-247667

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The Narmada river is a east west flowing river of about 1300 km length with a catchment area of 98,796 km^2. Since the study of Abbi et al (1970) at least two severe and two moderate storms have occurred in the basin necessitating review and updating of the hydrometeorology of the basin. The review has indicated that besides the moderate storms of August 1978 and August 1979, two severe storms have occurred in September 1970 and August 1973. Except for the storms in 1968 and 1970 which travelled all along the length of the basin, the tracks of other storms extended only upto half way of the basin. From the flood levels observed at Mortakka and Garudeshwar it was inferred that the moderate storms like those of 1950, 1978 and 1979 have resulted in floods of similar magnitude.

After the award of Narmada tribunal, the Irrigation Departments of Madhya Pradesh and Gujarat had contemplated construction of two major dams namely Narmada Sagar at Punasa in Madhya Pradesh and Sardar Sarovar at Gurudeshwar in Gujarat. The India Meteorological Department and Central Water Commission had conducted design storm studies for Narmada Sagar and Sardar Sarovar dams. To meet the special needs of the Narmada basin arising out of the elongated shape, large catchment area and movement of storms

parallel to the basin and in the same direction as the flood flows, synthesis of design storm by the sequential combination of different storms was proposed and accordingly the following design storm combinations were recommended for Narmada Sagar and Sardar Sarovar.

Narmada Sagar	28 Aug 1973	29 Aug 1973	30 Aug 1973	15 July 1944	
Sardar Sarovar	28 Aug 1973	29 Aug 1973	30 Aug 1973	5 Sep 1970	6 Sep 1970

Moisture maximisation studies were carried out by India Meteorological Department using 12 hours persisting dew point and second highest dew point. Also, return period analysis of maximum dew point temperature were carried out and a value of 1.35 has been recommended as against a value of 1.25 obtained by unpublished studies in Central Water Commission. Time distribution has been recommended by India Meteorological Department on the basis of eleven self recording raingauge stations located in and around Narmada basin.

Besides these studies, modelling of the moving storms which affected the catchment of Narmada basin was carried out using inter-station correlation coefficient of hourly rainfall at the recording raingauge stations in the basin. As the inter-station distance is large in comparison to the size of the rain cell the lag zero correlation was found to be not suitable for the analysis and the provision for carrying out inter- correlation with hourly shift upto a prescribed maximum lag has been made in the analysis. Four storms namely(i) 2-6 September 1970, (ii) 28-31 August 1973, (iii) 28-31 August 1978 and (iv) 6-10 August 1979 were considered in the analysis. The lag corresponding to optimum correlation analysis as indicated by the correlation analysis was compared with the physical movement of the storm as reported by India Meteorological Department and as revealed by the daily storm isohyetal pattern. The analysis indicates the lag zero correlation to be very poor as the relationship between interstation distance and lag zero correlation is very obscure. The storms of 1970,1978 and 1979 were noticed to have had comparable speeds while the 1973 storm was found to be relatively slower.

1.0 INTRODUCTION

Narmada basin with an area of 98,796 sq km is the largest and longest river basin in Central India. The Narmada river originates in the Amarkantak Plateau in Madhya Pradesh and travels westwards to fall into Arabian Sea near Bharuch in Gujarat. Tropical disturbances popularly known as cyclonic storms originating in the Bay of Bengal or over land near the east coast move in a west/north-westerly direction and travel over or along the Narmada basin. Sometimes they move along the length of the basin causing moderate to severe floods in the river. Because of the randomness associated with the track of the storms, the speed of storms moving across the land and the intensity of the storm system itself, the rainfall resulting from these storms varies in time and space. In this report some of the hydrometeorological aspects of the Narmada basin are presented and discussed.

2.0 REVIEW

The India Meteorological Department (1970) has prepared a report on the rainfall pattern of Narmada based on the 1950 normals. The mean monthly, seasonal and annual isohyetal maps together with coefficient of variation were prepared.

Abbi et al (1970) had studied the hydrometeorological aspects of Narmada in which the monthly and annual normals of rainfall and number of rainy days for the basin were worked out. Variability of monthly rainfall in the monsoon season (June-Sept) and of seasonal and annual rainfall was obtained. All major storms over Narmada basin during the period 1891-1968 were analysed by isohyetal method. Depth-area-duration and depth -duration curves for major storms in Narmada basin were prepared and envelope curves obtained. Peak discharge at Garudeshwar gauge site on 6th August 1968 has been computed from the precedent precipitation in the basin.

India Meteorological Department(1981) has carried out the design storm studies of Narmada basin and provided sub-catchment depths for major sub-catchments in Narmada basin upto Punasa (Narmada Sagar) and Sardar Sarovar dam sites. A maximisation factor of 1.35 has been recommended and the time distribution based on hourly rainfall data at eleven self recording raingauge stations located in and around Narmada basin has been recommended for four major sub-catchments of Narmada.

3.0 STATEMENT OF THE PROBLEM

After the award of Narmada tribunal, the states of Gujarat and Madhya Pradesh had initiated project proposals for the construction of Sardar Sarovar and Narmada Sagar respectively. Unlike other catchments, the elongated shape of the Narmada basin with its large catchment area and the movement of the storms in the same direction as that of the movement of the flood waters poses a unique problem for estimation of design storms. Besides, the fact that the storm covers only a portion of the basin on any single day, obviates the application of depth-area-duration values as the DAD values are only valid for regular shaped catchments.

Since the study of Abbi et al, at least two major tropical storms have affected the catchment in 1970 and 1973. Two other moderate storms have occurred in the years 1978 and 1979. The flood of 1973 was the highest at Mortakka, the gauge site close to the proposed Narmada Sagar and the flood of 1970 was an all time high at Garudeshwar where the flood waters entered the flood plain.

For understanding the behaviour of the rainfall runoff process in the Narmada basin a study of the climatology of rainfall, storms, their movement and the rainfall distribution over shorter durations is a pre-requisite. Without thoroughly understanding these aspects the mere application of design storm to estimate design floods would not provide the necessary insight into the flood occurrence and its lateral movement.

It was,therefore, felt imperative to study the hydro-meteorological aspects of Narmada basin including the whole gamut of design storm,behaviour of the rain storm over shorter duration and its movement in the basin.

4.0 DESCRIPTION OF THE STUDY AREA

The area of Narmada upto Bharuch is 98,796 sq km. 85% of this area is in Madhya Pradesh, 11.5% in Gujarat and the rest in the state of Maharashtra. The major tributaries along with their length and catchment area are listed in Table 1 and their sub-catchments shown in Fig.1 (a and b).

Table 1 - Major tributaries of Narmada river

Name of Tributary	Bank	Length of Tributary (km)	Catchment area (sq.km)	Distance of confluence with Narmada from source (km)
Burhner	Left	176	4070	246
Banjar	Left	182	3584	285
Hiran	Right	187	4480	461
Sher	Left	128	2867	494
Shakkar	Left	160	2266	542
Dudhi	Left	128	1523	571
Tendoni	Right	117	1613	598
Barna	Right	104	1766	602
Tawa	Left	171	6259	672
Kolar	Right	101	1331	709
Ganjal	Left	88	1907	752
Chhota Tawa	Left	168	4992	824
Kundi	Left	120	3776	938
Man	Right	88	1510	992
Uri	Right	74	1792	1029
Goi	Left	128	1869	1032
Orsang	Right	80	4032	1184
Karjan	Left	93	1472	1192

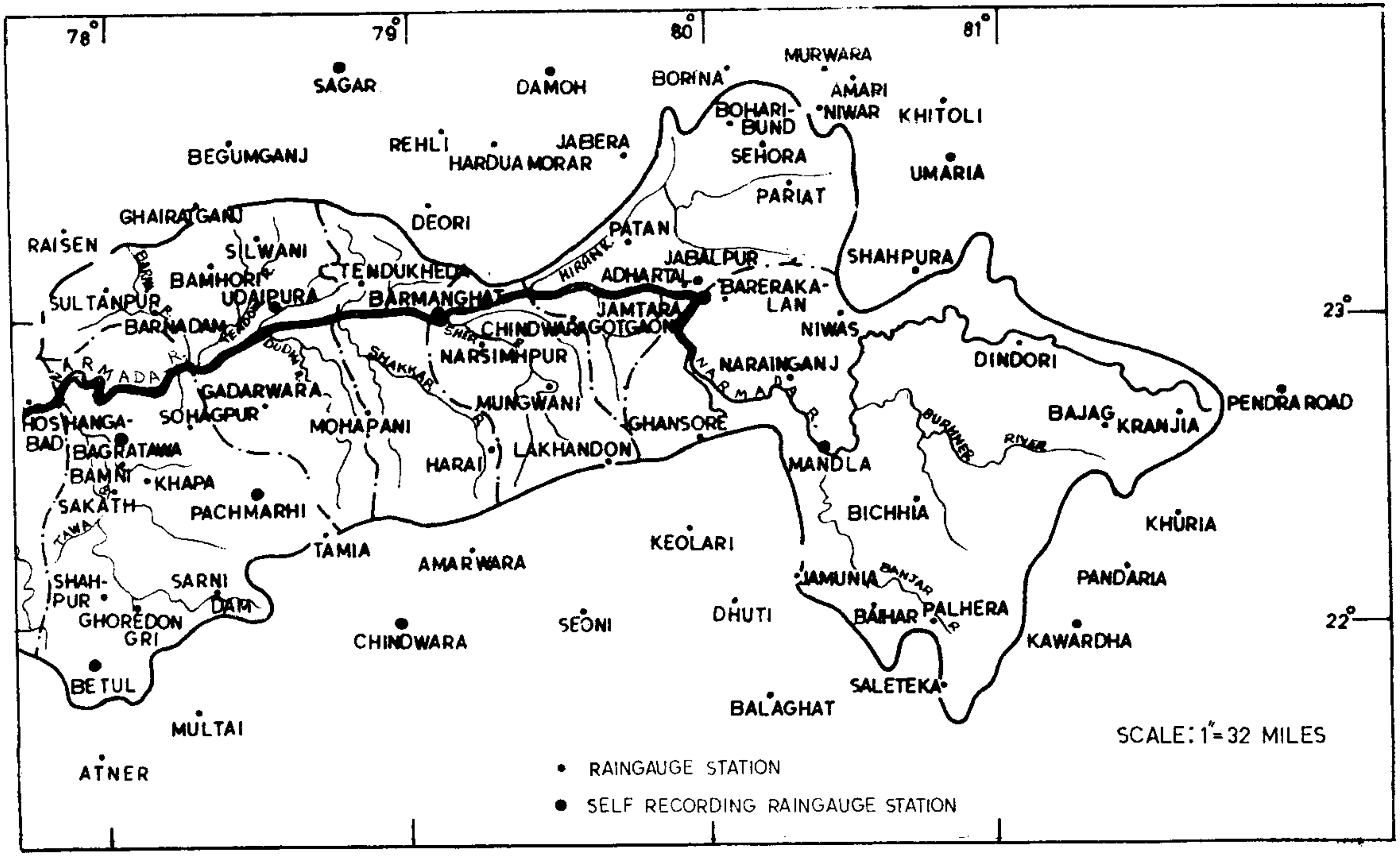

FIGURE 1(a) - CATCHMENT OF NARMADA UPTO HOSHANGABAD

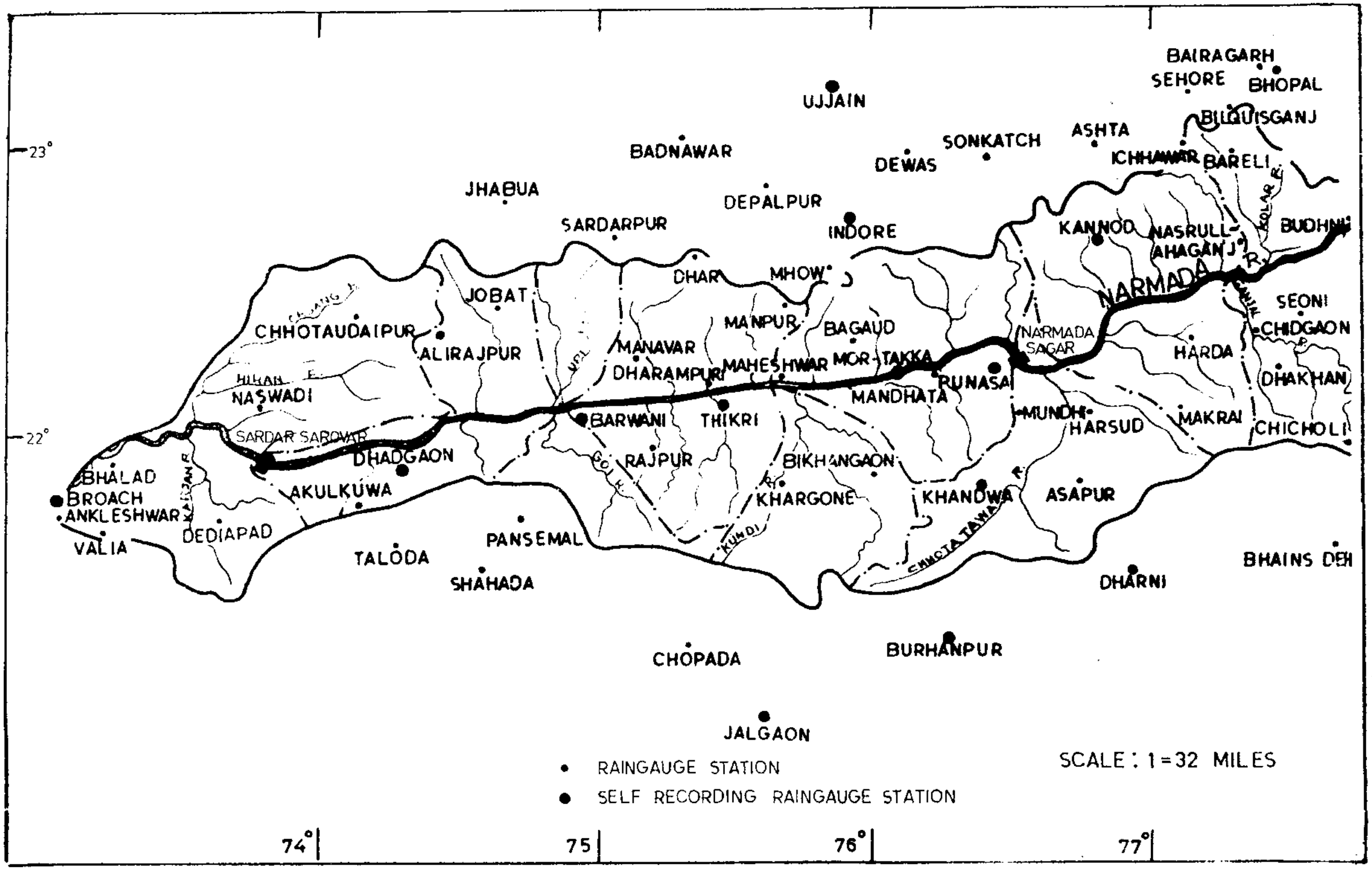

FIGURE 1(b)- CATCHMENT OF NARMADA BELOW HOSHANGABAD

4.1 Topography

The river rises in the Amarkantak plateau of Maikal range in Madhya Pradesh at an elevation of 1057 m.a.s.l. The river travels a distance of 1312 km before it enters Arabian Sea. Most of the basin is at an elevation of less than 500 m.a.s.l. A small area around Pachmarhi is at a height of more than 1000 m.a.s.l.

4.2 Climate

The climate of the basin ranges from sub-humid in the east to semi-arid in the west with pockets of humid and per-humid climates around higher hill reaches. The southwest monsoon is the principal rainy season accounting for nearly 90% of the annual rainfall. During this period a series of tropical storms originating from Bay of Bengal move west north westwards travel over or along the basin. Figures 2a to 2d show the frequency of storms and depressions over the Narmada basin in a $2\frac{1}{2}^{\circ} \times 2\frac{1}{2}^{\circ}$ grid covering the region from 20° to 25°N and $72^{\circ}30'$ to $82^{\circ}30'$E during the period from 1891-1970. As may be seen from the figures, the storms and depressions are more frequent and intense during August and September.

4.3 Rainfall

The normal (1901-1950)monthly and annual rainfall of long term rain gauge stations in and around Narmada basin is given in Table 2. The average annual rainfall over the basin is 123 cm. The isohyetal pattern of normal monsoon (Jun-Sept) and annual rainfall is shown in figures 3(a) and 3(b) respectively. Rainfall decreases from more than 150 cm in the east to 75 cm in the west. Variability of both seasonal and annual rainfall is small, and the coefficient of variation varies from 20 to 30%. The coefficient of variation of monsoon and annual rainfall is shown in Figures 4(a) and 4(b) respectively.

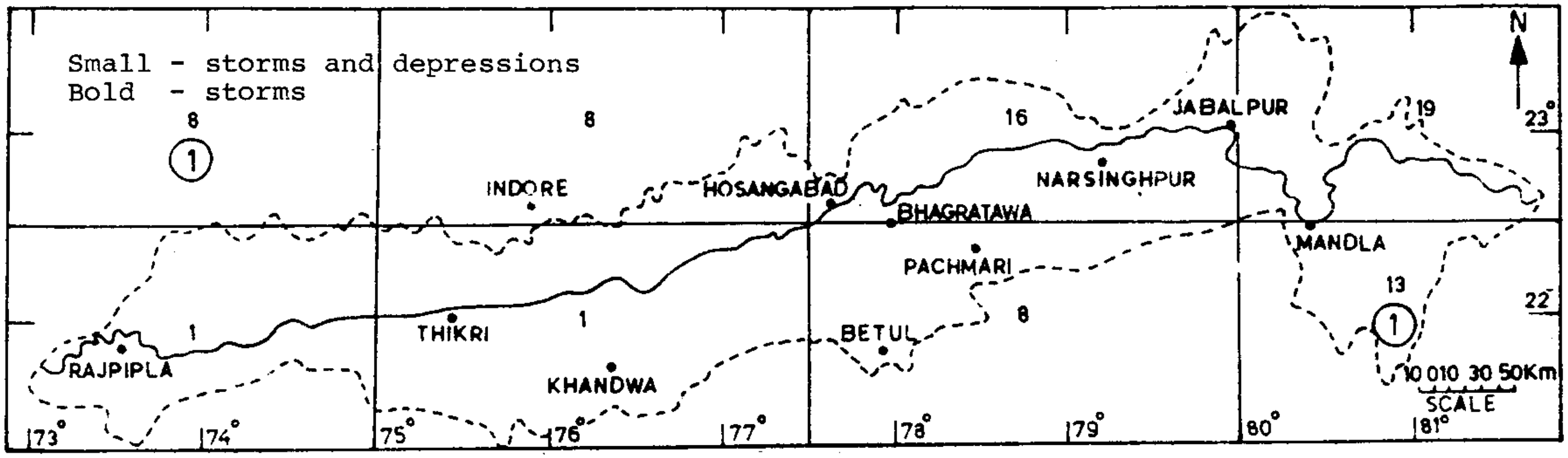

FIGURE 2(a)- FREQUENCY OF STORMS AND DEPRESSIONS- JUNE

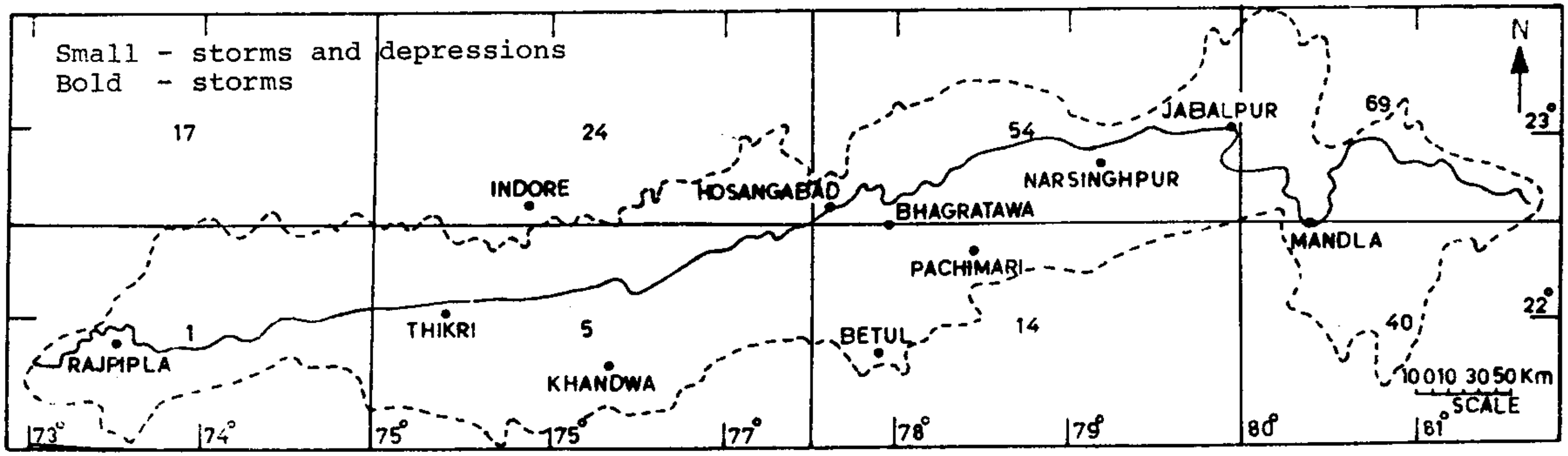

FIGURE 2(b)- FREQUENCY OF STORMS AND DEPRESSIONS- JULY

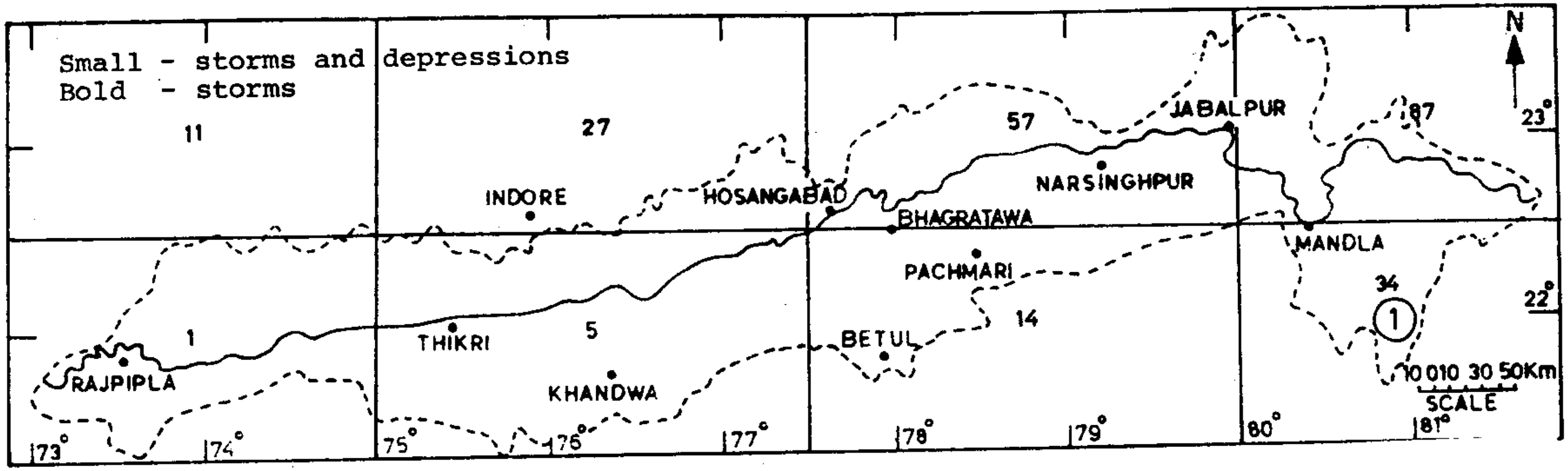

FIGURE 2(c)- FREQUENCY OF STORMS AND DEPRESSIONS - AUGUST

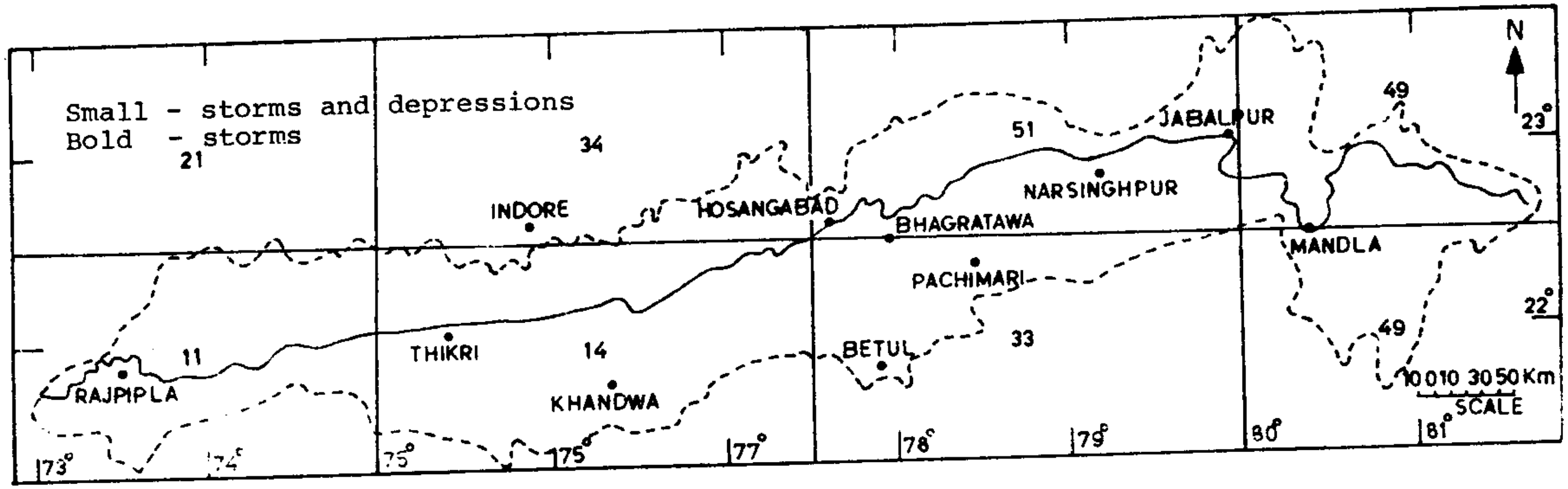

FIGURE 2(d)- FREQUENCY OF STORMS AND DEPRESSIONS- SEPTEMBER

Table - 2 Monthly and annual normal rainfall of raingauge stations in Narmada Basin

Station	No.of years	Rainfall mm												
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Kawardha	49	17.0	31.7	21.8	20.6	20.1	155.5	308.4	264.2	179.6	64.5	18.3	7.1	1108.8
Pendra Road	48	26.9	36.1	26.4	21.6	24.1	207.3	366.5	366.3	206.3	78.0	17.8	6.3	1383.6
Champa	6	21.6	19.1	15.0	12.9	8.4	176.5	438.7	493.3	239.0	56.6	14.5	3.6	1499.2
Mandla	50	27.7	36.3	25.9	18.0	15.5	206.0	487.4	416.1	215.4	54.4	16.3	9.4	1528.4
Narayanganj	50	24.6	35.3	21.3	12.5	14.2	192.3	471.7	430.8	210.6	55.1	12.9	8.1	1489.4
Dindori	50	29.5	33.8	25.4	17.0	17.0	188.5	452.1	432.8	208.8	61.5	18.0	8.4	1492.8
Shahpura	45	29.7	31.2	23.4	14.2	9.4	193.3	511.8	477.0	238.3	47.7	22.9	9.7	1608.6
Niwas	36	28.5	24.6	16.0	12.9	11.9	192.0	570.7	524.0	255.3	53.6	20.3	7.4	1717.2
Bajag	33	27.7	40.6	26.2	21.3	20.6	197.9	426.5	385.3	237.5	74.7	17.3	7.9	1483.5
Bichhia	33	31.2	34.3	22.6	18.8	13.5	180.3	579.6	487.2	257.8	59.4	16.0	8.6	1709.3
Karanjia	7	23.4	41.4	35.3	22.9	29.0	219.5	441.5	429.0	188.7	71.1	23.4	2.3	1527.5
Balaghat	50	16.0	27.2	20.1	18.0	14.7	211.1	570.5	487.9	231.1	54.9	16.0	5.1	1672.6
Baihar	50	19.6	34.5	24.6	19.1	14.0	191.0	507.7	449.6	215.9	61.0	16.0	8.9	1561.9
Jamunia	24	17.5	25.7	14.2	15.0	11.7	208.3	488.9	366.8	206.3	60.5	9.9	4.1	1428.9

Rainfall mm

Station	No. of Years	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Dhuti	24	15.2	39.1	25.9	26.7	13.7	240.5	591.1	431.5	227.1	70.9	14.2	10.9	1706.8
Saleteka	24	21.3	34.8	22.9	22.1	9.9	204.7	509.3	382.8	224.8	64.5	14.2	5.3	1516.6
Palhera	24	17.0	29.5	17.0	9.7	10.7	170.2	601.7	434.9	254.0	77.7	14.7	4.6	1641.7
Paraswada	24	24.9	32.8	12.9	21.1	10.4	182.6	636.5	481.3	250.4	70.6	10.4	7.6	1741.5
Lakhandon	50	24.4	35.6	24.1	16.3	16.3	170.7	379.5	322.8	201.4	52.1	18.3	8.4	1269.9
Ghansore	29	30.2	36.6	22.1	18.5	10.7	178.3	451.1	355.9	209.3	57.4	17.8	9.1	1397.0
Barerakalan	24	24.4	18.3	7.9	3.6	2.3	120.4	446.5	354.1	192.8	34.0	10.7	6.3	1221.3
Amari	24	31.0	26.7	11.4	6.1	6.9	134.4	391.9	344.2	169.2	49.8	14.7	8.6	1194.9
Jabalapur	50	24.4	24.4	15.5	9.9	14.5	157.0	483.4	416.6	211.3	46.5	18.8	8.4	1430.7
Sihora	50	22.1	21.6	15.0	7.4	5.8	126.5	437.1	416.3	206.5	35.3	18.3	8.4	1320.3
Pariat	24	25.4	22.1	13.5	5.6	1.5	167.6	597.7	432.1	243.6	42.7	16.5	14.2	1582.5
Patan	38	22.9	21.6	12.9	8.9	1.2	148.6	402.3	388.1	195.3	46.7	12.2	8.1	1279.8
Baharibund	24	33.3	20.8	11.7	5.3	2.0	123.9	405.9	340.6	158.7	40.6	15.2	8.1	1166.1

Rainfall mm

Station	No. of Years	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Niwar	24	27.7	23.9	10.4	3.8	3.6	142.7	389.6	393.5	185.2	46.0	15.7	9.4	1251.5
Narsimhapur	50	14.0	19.8	13.7	8.4	9.1	139.7	395.2	371.9	210.8	37.1	15.0	6.3	1241.0
Gadarwara	50	16.8	14.5	10.7	4.8	10.2	143.8	413.8	363.5	225.3	41.7	16.8	6.3	1268.2
Moh apani	50	13.2	17.5	12.9	5.6	12.9	139.9	478.3	417.8	240.5	51.3	19.3	14.7	1423.9
Chhindwara	46	17.5	21.8	12.9	8.6	10.9	162.3	387.6	368.1	203.2	41.7	18.8	8.4	1261.8
Tendukhera	46	17.8	12.9	10.4	5.3	11.2	156.0	431.3	403.9	202.9	32.3	18.0	7.6	1309.6
Chindwara	50	19.6	30.0	18.8	10.7	16.0	160.0	320.8	226.6	179.3	47.7	23.4	10.7	1063.6
Harrai	49	19.6	25.1	20.3	10.4	14.2	152.7	381.5	337.8	215.4	48.5	21.3	7.6	1254.5
Tamia	49	20.1	24.4	20.3	10.9	17.8	199.1	612.1	513.3	310.1	62.5	24.4	8.6	1823.6
Amarwara	37	22.6	27.7	22.9	14.2	18.8	189.7	333.8	262.6	174.7	71.4	23.6	8.1	1170.1
Hoshangabad	50	14.5	11.9	6.3	3.3	11.4	143.3	439.2	396.5	215.4	28.5	21.3	10.7	1302.3
Harda	50	11.2	7.1	6.3	1.8	11.2	141.7	385.6	285.5	204.2	40.4	21.8	7.4	1124.2
Seoni	50	14.7	8.4	6.9	1.3	7.4	160.3	459.5	360.9	227.3	30.0	21.1	9.7	1307.5
Sohagpur	50	15.2	12.2	8.6	3.3	9.9	153.4	442.2	387.9	245.6	35.8	19.1	6.6	1339.8
Pachmarhi	50	22.1	24.6	14.7	9.7	16.5	201.9	726.2	643.9	363.2	63.3	28.2	8.6	2122.9

Rainfall mm

Station	No.of Years	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Makrai	45	15.0	7.4	7.9	2.8	9.4	182.4	471.2	377.7	259.1	35.3	23.1	7.4	1398.7
Betul	50	18.5	16.3	20.6	8.1	11.9	160.8	374.7	303.5	194.1	48.5	27.2	8.6	1192.8
Multai	50	15.5	19.6	19.3	11.9	13.2	163.3	294.1	227.3	161.3	50.8	26.2	8.9	1011.4
Shahpur	50	27.4	20.6	15.2	5.1	11.9	150.6	363.2	297.4	185.4	37.6	20.3	7.4	1142.1
Chicholi	50	17.5	12.5	12.5	5.3	14.5	149.9	375.4	294.6	180.3	47.0	30.0	6.1	1147.6
Atner	45	12.5	18.8	12.5	6.3	12.5	142.2	277.6	188.0	151.1	52.3	31.0	9.4	914.2
Bhainsdehi	40	14.5	14.5	13.7	11.2	12.5	161.5	335.5	241.3	180.9	66.8	36.1	8.4	1094.9
Bhopal	22	17.0	5.3	8.9	3.6	10.2	148.3	490.7	277.6	240.0	31.7	20.6	6.3	1260.2
Sehore	22	10.2	4.8	7.4	1.8	5.6	171.5	519.4	390.1	252.2	30.5	14.7	4.1	1412.3
Ichhawar	32	14.0	6.1	3.6	8.5	14.7	150.9	431.8	356.1	204.2	31.5	18.8	8.9	1242.1
Nasrullaganj	27	12.7	7.1	5.6	2.0	12.2	142.2	496.5	359.9	217.2	39.9	28.7	10.9	1334.9
Bilquesganj	13	15.7	4.3	3.3	0.0	8.9	195.3	513.6	343.7	185.7	34.0	11.4	6.1	1322.0

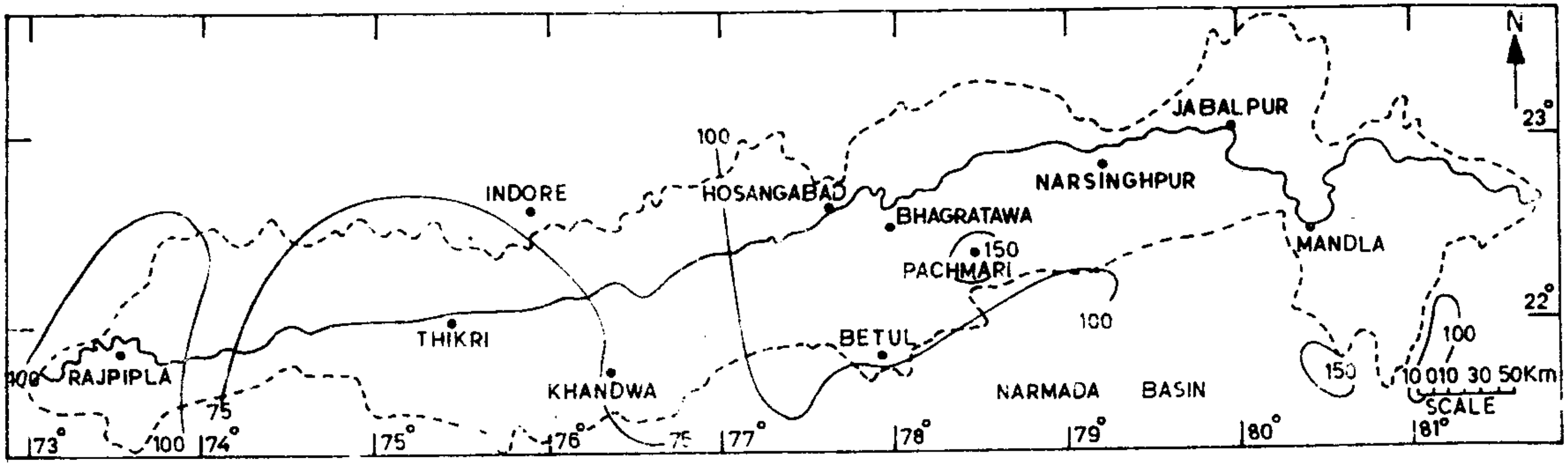

FIGURE 3(a)- NORMAL MONSOON (JUNE-SEPTEMBER) RAINFALL-Cm

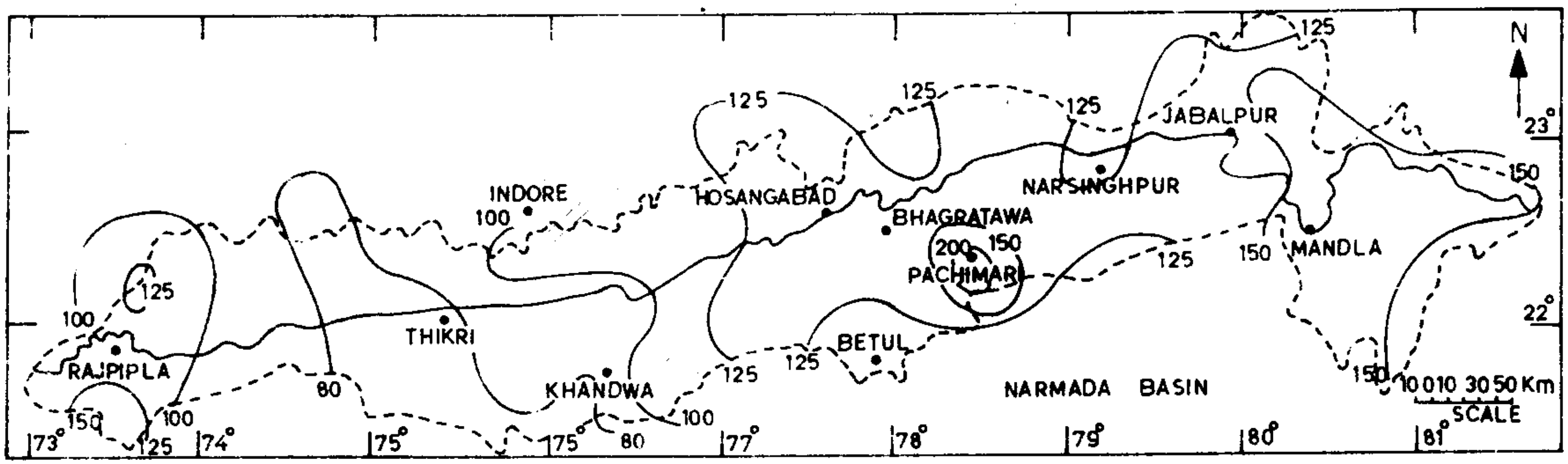

FIGURE 3(b)- NORMAL ANNUAL RAINFALL- Cm

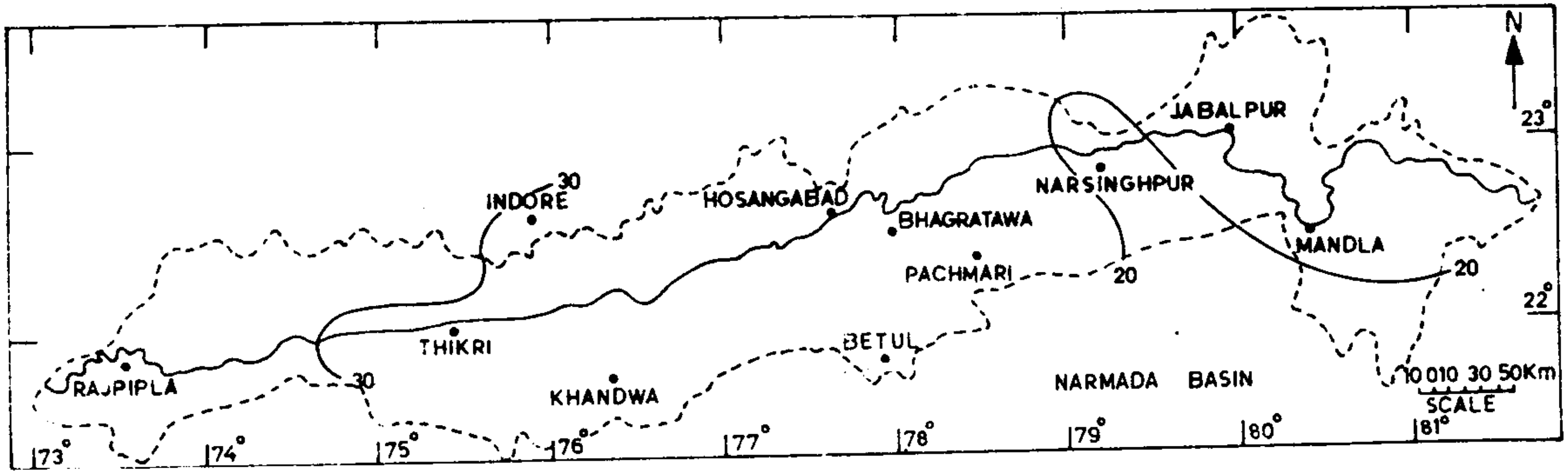

FIGURE 4(a)- COEFFICIENT OF VARIATION OF MONSOON (JUNE-SEPT) RAINFALL-PERCENTAGE

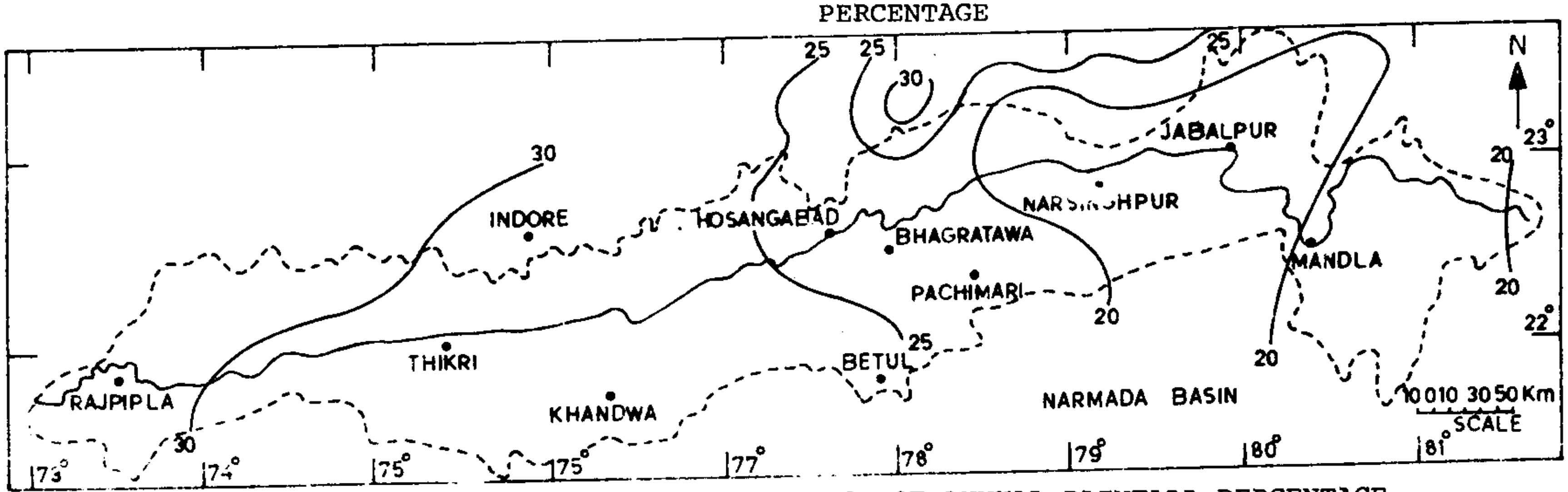

FIGURE 4(b)- COEFFICIENT OF VARIATION OF ANNUAL RAINFALL-PERCENTAGE

5.0 AVAILABILITY OF DATA

There are about 150 non-recording and about 50 recording raingauge stations in and around the Narmada basin. Their locations are shown in Fig.1

5.1 Daily Rainfall Data

Printed records of daily rainfall data are available upto 1975 for Madhya Pradesh gauges, which the National Institute of Hydrology has purchased from Gwalior. The Institute has also by payment obtained data for all gauges in and around Narmada basin from India Meteorological Department by transferring to magnetic tapes. The rainfall data on tapes are available for stations in Madhya Pradesh for the period 1965-72, Maharashtra for the period 1965-77, Gujarat for 1963-1973 and for India Meteorological Department observatories for the period 1965-79.

5.2 Hourly Rainfall (SRRG) Data

Most of the data of self recording raingauges is recorded by self recording rain gauges maintained by India Meteorological Department. Data of majority of the SRRG is available only after 1970. The list is given in the Table 3. The National Institute of Hydrology has obtained by payment the hourly rainfall data of all the India Meteorological Department SRRG's in and around Narmada for the period 1969-79 from India Meteorological Department on tape. Data of self recording raingauge stations maintained by other agencies and of later years of India Meteorological Department stations received from NPDDC, Gujarat were processed to make them computer compatible.

Table 3 - List of self recording raingauge stations in and around Narmada Basin

State	District	S.R.R.G. Stations	District	S.R.R.G. Stations
Madhya Pradesh	Rajnandgaon	Kawardha	Hoshangabad	Hoshangabad
	Bilaspur	Pendra Road		Bagratawa
	Champa	Champa		Tawa Dam
	Mandla	Mandla		Pachmarhi
	Shahdol	Umaria		Chhidgaon
	Balaghat	Malanjkhand	Bhopal	Bairagarh
	Jabalpur	Jabalpur	Raisen	Barna Dam
		Jamtara		Silvani
	Seoni	Lakhandon	Betul	Betul
		Seoni		Sarni Dam
	Jabalpur	Sihora	Nimar	Khandwa
	Damoh	Damoh		Burhanpur
	Narasimhapur	Narasimhapur		Punasa
				Mandhata
		Gadarwara		Mortakka
		Mohapani	Dewas	Kannode
		Bermanghat	Indore	Indore
		Bamhori	Khargone	Mandleshwar
	Chindwara	Harai		Thikri
		Chindwara		Barwani
Maharashtra	Amaravati	Dharni	Ujjain	Ujjain
	Jalgaon	Jalgaon	Jhabua	Alirajpur
Gujarat	Broach	Rajpipla	Dhule	Dhadgaon
		Kewadia-Colony		

6.0 METHODOLOGY

6.1 Selection of Rainstorms

For selecting the design storm a number of rain storms were analysed. For this purpose, the daily rainfall data of raingauge stations in and around the basin were scrutinised. Keeping a threshold value of daily rainfall of 10 mm, all such rain spells during which a number of stations recorded rainfall equal to or above the threshold on two days or more were selected. To select the severest rain storms from out of these storms, arithmetic average of the rain storm over hypothetical areas were computed and the severe storms were selected for isohyetal, depth-area-duration and depth-duration analysis.

6.2 Design Storm For Narmada Basin

The Narmada basin being elongated in shape and covering a large area, to facilitate the design flood estimation, the catchment upto Narmada Sagar (area 61642 km^2) was divided into 13 sub-catchments and the catchment between Narmada Sagar and Sardar Sarovar (area 26358km^2) was divided into eight sub-catchments by the Central Water Commission. The past experience has shown tha the storms move parallel to the catchment and as the flood waters resulting from rainfall over the upstream catchment travel downstream, rain occurs in the down stream catchment thus accentuating the flood flows into a critical peak flow. The conventional methods of adopting DAD values or carrying out storm transposition and depth-duration studies would not yield the design flood commensurate with the potential of Narmada basin. A site specific storm analysis, therefore, had to be carried out to fabricate a synthetic design storm.

6.3 Synthetic Design Storm

As part of the methodology for design storm estimation, WMO Technical note 98 has recommended the use of a sequence of two storms or periods of rain that have affected the basin. In this process, the elapsed time between storms is shortened perhaps from years to a few days. More elaborate time sequence development included transposition of one or more storms. Further maximisation is provided by adjustment of one of the storms for maximum moisture. A detailed study of the meteorological and hydrological characteristics of storms and floods in Narmada basin indicated the possibility of a five day storm occurring over the basin and sustaining the flood at the proposed dam sites. As would be seen later, storms having similar tracks could have similar rainfall distribution in time and space and produce floods of identical magnitude. On this basis, it was thought feasible to implant a day or days' rainfall from one storm into the sequence of another storm without disturbing the sequence as guided by its entry into and exit from the basin.

6.4 Maximisation of Synthetic Storms

The WMO operational Hydrology Report No 1 recommended two types of maximisation for enhancing depths of rain storms. (i) maximisation for moisture and (ii) maximisation for wind speed. The rainfall process in the non-orographic areas is conceived of as a system where in air converges radially inwards at lower levels and leaves the system radially outwards at large heights thus getting cooled, saturated adiabatically in the process.

Besides the WMO report, the US Weather Bureau Hydromet report on Mekong Basin (1970) advises against application of moisture maximisation in the tropics since the procedure has, originally, been developed for the temperate latitudes. In tropical climates where moisture is generally near the saturation levels at the time of storm occurrence there is no justification for storm maximisation.

However, moisture maximisation continues to be applied in practice for obtaining PMP in India by India Meteorological Department and Central Water Commission.

During the training programme of Shri Ramasastri in National Weather Service, USA discussions were had with Mr John Miller, Chief, Water Management information division on the need for applying moisture maximisation to synthetic storms and the procedure to be followed in case it was to be maximised. Mr. Miller suggested that the sequential combination of two storms only takes care of the small storm sample available over the area and does not provide the PMP. A weighted maximisation factor or alternatively an arbitrary isohyetal boundary could be considered for this purpose. Since the storms are of a moving nature, for the purpose of computing the maximisation factor, the storm dew point temperature need to be collected from the region of moisture source feeding the storm on a given day (WMO operational Hydrology Report No 1). This would, naturally, take into consideration the different moisture regimes which can be expected at different geographical locations due to distance from the sea, height above mean sea level and orographic considerations.

6.5 Time Distribution

Unlike catchments with small areas or fan shape, the elongated shape of the catchment, its large area and movement of storms along the basin calls for exercising care while applying the distribution to the various sub-catchments. As was done in the case of time distribution for the design storm of Mahanadi upto Hirakud (Central Water Commission,1976), the time distribution for each or a group of the sub catchments in the Narmada basin is to be evolved separately incorporating the necessary lag from upstream to down stream while keeping a critical sequence of rainfall blocks in each of the sub-catchments.

Though, the self recording raingauge network is really not adequate, there is at least one SRRG in a number of sub-catchments. In such of those sub-catchments where a SRRG is not available, the time distribution evolved for the neighbouring catchment with a SRRG could be adopted for the purpose of deriving shorter time increments of sub-catchment rainfall depths.

6.6 Mathematical Modelling of moving storm

The movingstorms over the basin were modelled based on the correlation between hourly rainfall at self recording raingauge stations by assuming non-stationartiy in time and stationarity in space. The inter-station distance between neighbouring stations being large in size as compared to the size of the rain cell, inter-station correlation at lag zero was found not suitable and the movement of storm across the basin is modelled through inter-station correlation analysis with time lag introduced at input and during computations. A computer program was prepared to compute the inter-station correlation with successive increments of lag upto a specified maximum lag.

7.0 ANALYSIS

After preliminary catchment average rainfall analysis, the following ten storms were found to be severe. They are given here in chronological order.

(i) 1-3 August 1913

(ii) 19-21 Sept 1926

(iii) 12-16 July 1944

(iv) 27-29 July 1950

(v) 8-9 September 1961

(vi) 3-6 August 1968

(vii) 2-6 September 1970

(viii) 29-31 August 1973

(ix) 26 August - 2 September 1978

(x) 6-10 August 1979

The storm tracks of the storms listed above are shown in Figure 5. As may be seen in the figures, except 1961 and 1970 all other storms were Bay depressions.

7.1 Floods Associated with the Severe Historical Rain Storms

Some of the highest peak stages observed at Mortakka and Garudheshwar were associated with the above floods. The peak stages along with their date of occurrence are given below.

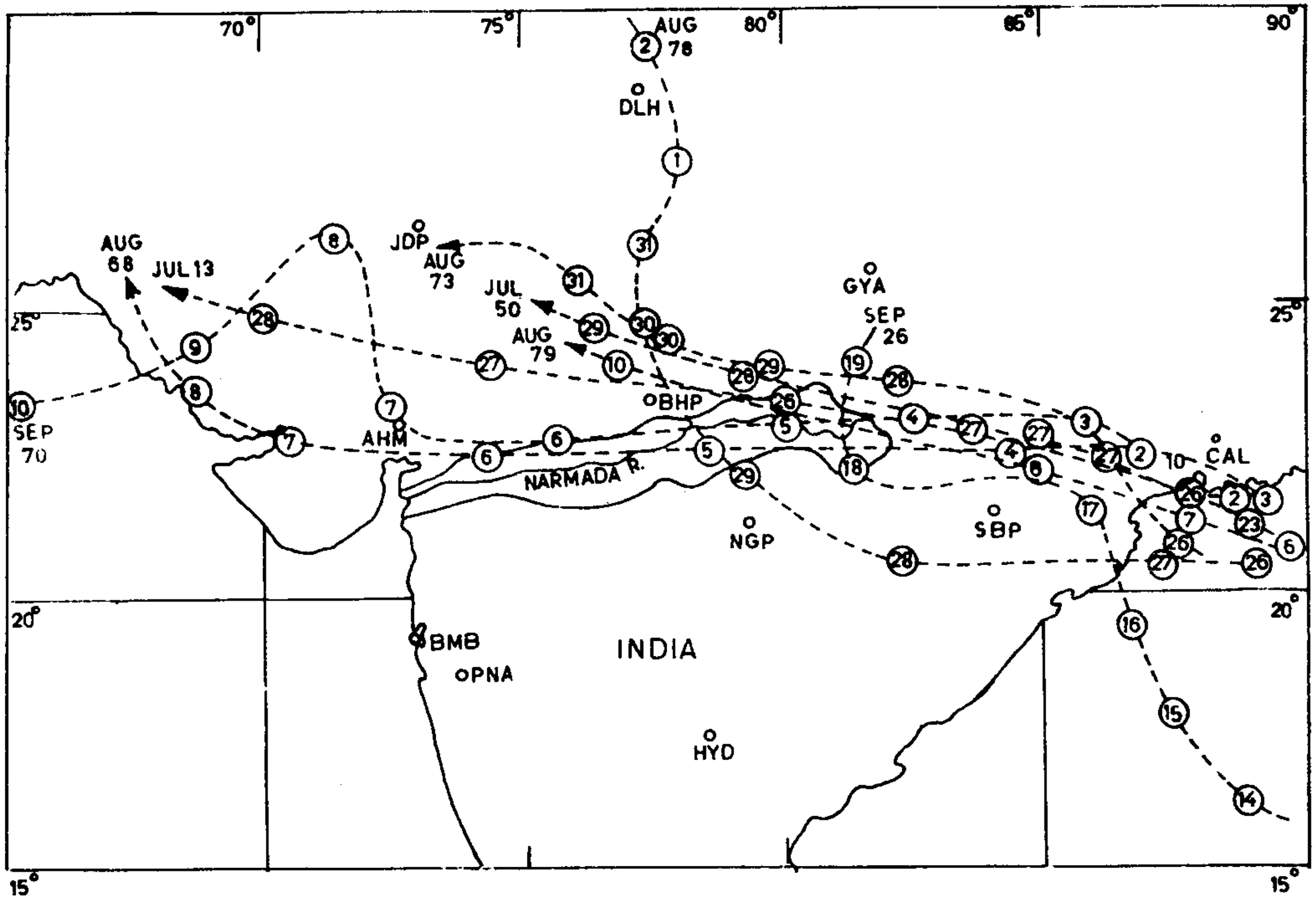

FIGURE 5- TRACKS OF STORMS AND DEPRESSIONS OVER NARMADA BASIN

Peak stage at Mortakka (metres)		Peak stage at Garudeshwar (metres)	
29 July 1950	15.03	30 July 1950....	6.94
10 Sept 1961	19.20	17 Sept 1961....	7.76
6 Aug 1968	14.78	6 Aug 1968...	27.44
6 Sept 1970	16.76	6 Sept 1970...	29.65
31 Aug 1973	20.67	31 Aug 1973...	28.18
29 Aug 1978	14.87	30 Aug 1978...	22.33
10 Aug 1979	14.05	10 Aug 1979...	21.55

7.2 Depth-duration Analysis

Isohyetal analysis of some of these storms were carried out and the depths of rainfall over each of the sub-catchments in the catchment upto Narmada Sagar and Sardar Sarovar were computed by depth-duration analysis. In table 4, the overall catchment depths for the catchment upto Narmada Sagar and the catchment between Narmada Sagar and Sardar Sarovar are presented.

7.3 Transposition of Storms from Neighbouring Catchments

The possibility of transposing severe storms which have occurred in the neighbouring catchments of Mahanadi in the east, Son,Ken,Betwa in the north, Mahi and Chambal in the west and Tapi in the south was examined. The severe storms in Mahanadi basin were those of June 1925, June 1936 and July 1958 (Gole et al,1976). In the catchments of Son and Ken, the storm of 25-26 June,1946 with centre at Pushparaj-

Table 4 - Daily rainfall depths of selected storms over Narmada Basin

No.	Storm Dates	Average depths in mm: Catchment upto Narmada Sagar	Average depths in mm: Catchment between Narmada Sagar and Sardar Sarovar
1.	1st August 1973	52.3	7.9
	2nd August 1973	113.3	43.2
	3rd August 1973	48.0	37.6
2.	19 Sept 1926	67.0	3.0
	20 Sept 1926	96.0	13.0
	21 Sept 1926	88.0	2.0
3.	12 July 1944	29.5	8.9
	13 July 1944	56.6	18.3
	14 July 1944	79.0	69.9
	15 July 1944	90.2	87.4
	16 July 1944	40.1	61.2
4.	27 July 1950	16.0	10.4
	28 July 1950	78.0	63.0
	29 July 1950	52.6	22.6
5.	8 Sept 1961	37.0	2.9
	9 Sept 1961	118.0	3.8
	10 Sept 1961	39.0	1.4
6.	2 Sept 1970	45.0	6.6
	3 Sept 1970	44.7	10.2
	4 Sept 1970	34.3	13.0
	5 Sept 1970	36.8	79.8
	6 Sept 1970	29.5	118.4
7.	28 August 1973	33.8	2.0
	29 August 1973	100.6	7.1
	30 August 1973	99.8	63.5
	31 August 1973	9.1	87.6
8.	24 August 1978	22.2	0.6
	25 August 1978	43.9	22.8
	26 August 1978	31.1	45.1
	27 August 1978	11.6	12.5
	28 August 1978	15.6	66.4
	29 August 1978	37.1	73.6
	30 August 1978	23.1	6.6

garh was severe. The storm of 27-29 July 1965 with centre at Bairagarh was severe in Betwa catchment (Dhar et al,1978). The July 1927 storm and August 1973 storms were severe near the catchments of Mahi and Chambal (Dhar et al 1974,1975). In the catchment of Tapi, there were two severe storms, one during 13-15 September 1959 with Centre at Talhera and the other from 4 to 6 August 1968 with centre at Yavel.

The storms of June 1925, June 1936 and July 1958 in Mahanadi basin have occurred in the lower Mahanadi with centres at Phulbani, Bulandarpara and Titlagarh respectively (Rao et al,1972). In view of their proximity to sea, the moisture source, these could not be considered for transposition to Narmada basin which is far from the east coast.

The storm of 26-28 July 1927 has occurred near Dakor-Ahmedabad west of the Mahi Basin and down stream of Dharoi in Sabarmati. The storm location is very near to the Gulf of Cambay, the moisture source. The storm could only be transposed downstream of Barwani in the Narmada basin because of the presence of 450-600m ridge to the north of the catchment upstream of Barwani. This, naturally, would be of little consequence from the flood point of view because of the small catchment area influenced by the storm upstream of Garudeshwar.

The storm of 4-6 August 1968 which produced record flood at Ukai in Gujarat had two rain centres in the range of 400-500 mm at Yaval and Navapur respectively. Yaval is at an elevation of less than 300 m south of the ridge with tops above 600 m. Similarly, the centre at Navapur is at a height of less than 150 m south of the ridge where the tops are above 900 m in the Satpura range. As such, these centres which were in the valley region could not be transposed across the barrier involving 400-700 m of lifting which violates the orographic influence which guides the precipitation intensity and its distribution in time and space.

These considerations have broadly led to the decision against transposition of these storms into Narmada basin. In the case of other storms, though some of them were transposable, their areal extent being small, were found to be not critical enough for design purposes.

7.4 Possible Combination of Synthetic Design Storm for Narmada Sagar

For the purpose of design storm estimation, the catchment upto Narmada Sagar (61642 km^2) is considered to experience a storm of 4 days duration. After a careful examination of the daily rainfall pattern for the catchment of Narmada Sagar as a whole and the sub-catchment depths separately, the first three days of August 1973 storm i.e. 28,29 and 30th August and the 4th day of July 1944 storm i.e. 15 July were considered to be a critical combination. Alternatively, the first and fourth day of July 1944 storm i.e. 12th and 15th July with 29th and 30th August 1973 as second and third day could be tried.

As may be seen from the following table, the depths of 12 July 1944 are only marginally less than 28 August 1973.

	Depth in mm 1st Day	2nd Day	3rd Day	4th Day
First Alternative	33.8 (28 Aug 73)	100.6 (29 Aug 73)	99.8 (30 Aug 73)	90.2 (15 July 44)
Second Alternative	29.5 (12 July 44)	100.6 (29 Aug 73)	99.8 (30 Aug 73)	90.2 (15 July44)

The possibility of using the Sept. 1961 storm in combination with Aug.1973 has also been examined in view of the critical depths of the Sept.1961 storm over Tawa catchment. As may be seen from below, the Sept.1961 storm is essentially a 3 day storm with the highest 1 day rainfall concentrated on the 2nd day and its depth is only marginally higher than that of 29th August 1973 thereby not providing scope for the synthetic combination.

	Depths in mm 8th	9th	10th
Rainfall depths of Sept. 1961 storm upto Narmada Sagar	37.0	118.0	39.0

Another possibility was the use of Sept.1926 storm in combination with July 1944 or Aug 1973 storms. The Sept 1926 storm was a late September (19-21) storm by which time the monsoon generally withdraws from Central India and the prevailing westerties at surface and in the upper air force the system to recurve. As may be seen from the storm track in Fig.5, the storm has practically remained stationary from 19-21 Sept over Madhya Pradesh east of Narmada basin. Since the conditions for sequential combination assumed in section 6.3 are valid for only east-west moving storms having similar or near similar tracks,the stationary recurving storm of Sept 1926 does not fit into the sequential combination.

Depths in mm			
Rainfall depths of Sept.1926	19th	20th	21st
storm upto Narmada Sagar	67.0	96.0	88.0

Even from the point of view of magnitude as may be seen from above, the Sept 1926 storm does not have critical depths on a single day. They were rather evenly distributed on all three days. Such a storm, however, would be useful from the point of view of building up necessary antecedent conditions. But in view of the storm being a late September storm it would be unreasonable to expect the storm to precede the July,August or early September storm to which the 1944, 1973 and 1970 storms respectively belong.

7.5 Possible combination of Synthetic Design Storm for Sardar Sarovar

Both from experience of past storms and due to the extra catchment of 26,358 km^2 between Narmada Sagar and Sardar Sarovar, the catchment upto Sardar Sarovar is considered to experience a 5 day storm for the purpose of design storm estimation.

For arriving at a 5 day critical storm upto Sardar Sarovar, two combinations were found viable and critical from the flood point of view. They are (i) the first three days of Aug 1973 storm i.e. 28,29th and 30th August followed by 5 and 6th September 1970 and (ii) the first three days of August 1973 followed by 15th and 16th July 1944. The synthetic or near similar tracks, the stationary recurving storm of Sept 1926 does not fit into the sequential combination.

Depths in mm			
Rainfall depths of Sept.1926	19th	20th	21st
storm upto Narmada Sagar	67.0	96.0	88.0

Even from the point of view of magnitude as may be seen from above, the Sept 1926 storm does not have critical depths on a single day. They were rather evenly distributed on all three days. Such a storm, however, would be useful from the point of view of building up necessary antecedent conditions. But in view of the storm being a late September storm it would be unreasonable to expect the storm to precede the July, August or early September storm to which the 1944, 1973 and 1970 storms respectively belong.

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For arriving at a 5 day critical storm upto Sardar Sarovar, two combinations were found viable and critical from the flood point of view. They are (i) the first three days of Aug 1973 storm i.e. 28,29th and 30th August followed by 5 and 6th September 1970 and (ii) the first three days of August 1973 followed by 15th and 16th July 1944. The synthetic design storm pattern for both the alternatives is given below:-

Synthetic Design Storm Sequence for Sardar Sarovar

Alternative I			Depths in mm		
Catchment	28 Aug 1973	29Aug 1973	30 Aug 1973	5 Sept 1970	6 Sept 1970
a. Total Catchment upto Narmada Sagar	33.8	100.6	99.8	36.8	29.5
b. Narmada Sagar to Sardar Sarovar	2.0	7.1	63.5	79.8	118.4
c. Total catchment upto Sardar Sarovar	28.0	63.0	80.0	61.0	72.0

Alternative II			Depths in mm		
Catchment	28 Aug 1973	29 Aug 1973	30 Aug 1973	15 July 1944	16 July 1944
a. Total catchment upto Narmada Sagar	33.8	100.6	99.8	90.2	40.1
b. Narmada Sagar to Sardar Sarovar	2.0	7.1	63.5	87.4	61.2
c. Total catchment upto Sardar Sarovar	28.0	63.0	80.0	99.0	44.0

From the overall depths though it might look as if the second alternative is more critical it would in actuality only produce slightly more volume than the first alternative. For maximum flood peak,however, the first alternative would be more critical because of the comparatively larger depths of the first combination than those of the later in the intermediate catchment on the last two days.

7.6 Moisture Maximisation for the Design Storm

Moisture maximisation analysis are carried out using selected persisting storm dew point at each station in the path of moisture flow in accordance with the position of storm on the particular day to the depth of which the moisture maximisation was to be applied. Moisture maximisation studies were carried out by India Meteorological Department using 35 years of dew point temperature data at eight stations in the path of moisture flow.

These studies were discussed at the meetings held in Narmada PP Cell during August 1982 and the India Meteorological Department was requested to review the studies considering:-

(i) persisting 12 hr dew points for the storm duration and second highest isolated dew point records.

(ii) the return period analysis of the maximum dew point temperature series of individual stations.

7.7 Time Distribution for the Design Storm recommended by India Meteorological Department

The India Meteorological Department in consultation with Central Water Commission had suggested a time distribution for use over Narmada catchment. The average time distribution of storm rainfall for different sub-divisions of Narmada catchment has been computed based on the analysis of the time distribution of 11 stations namely Mandla Jabalpur,Betul,Bagra Tawa, Chindwara,Pachmarhi,Khandwa,Indore Thikri,Punasa and Nandurbar. The distribution of 48 and 72 hrs for different sub-catchments as recommended by I.M.D. is given in Table 5.

7.8 Studies of Modelling of Moving Storm Carried out at National Institute of Hydrology

For the purpose of the present analysis, one storm each associated with the floods of 1970,1973,1978 and 1979 in Narmada were considered. The availability of hourly rainfall data as mentioned in Section 5.2 was limited in 1970 and 1973. For the year 1978 it was,however, better though, in 1979,the data for only a few stations has been received.

The hourly rainfall data were scrutinized by visual observation for each flood event and the associated storm period at each SRRG station was identified. This scrutiny revealed the approximate time lag in rainfall occurrence from station to station. Hourly rainfall data were input into the inter-station correlation program described in Section 6.6 incorporating the time lag already noticed from visual observation. As indicated already, the program further lags the data at station downtrack of the storm by increments of one time step (1 hour) upto a maximum specified lag which was taken as 18 hrs in this case. The inter-station correlation was carried out for all pairwise combinations of recording rain gauges.

Table 5 - Time distribution of storm rainfall for different sub-catchments in Narmada basin

Values in percentage

Hours	Catchment upto Narasimhapur		Catchment between Narasimhapur and Punasa		Tawa Catchment		Catchment between Punasa and Gardueshwar	
	48	72	48	72	48	72	48	72
3	30	23	22	15	23	18	30	19
6	40	31	31	22	33	28	41	27
12	48	37	41	29	42	35	50	33
15	56	43	49	35	49	42	57	39
18	62	47	55	41	55	49	64	44
21	68	52	61	45	62	54	69	49
24	73	57	65	51	67	57	75	53
27	78	61	71	55	71	63	79	57
30	82	64	75	57	75	66	83	61
33	85	68	80	63	79	69	87	66
36	88	71	84	67	83	72	90	69
39	91	75	89	71	88	75	93	73
42	93	77	92	75	90	78	95	77
45	95	81	95	78	91	80	98	79
48	98	83	97	81	97	83	99	83
51	100	85	100	84	100	85	100	85
54		87		87		88		89
57		90		89		90		91
60		93		91		92		93
63		95		94		94		97
66		96		96		96		97
69		97		97		97		99
72		99		99		99		99
		100		100		100		100

8.0 RESULTS

8.1 Synthetic Design Storm for Narmada Sagar and Sardar Sarovar

Based on the analysis and after considering the possibilities of transposition and the different alternate synthetic combinations of storms for design purposes the following storms were recommended for Narmada Sagar and Sardar Sarovar which were agreed upon by India Meteorological Department and Central Water Commission during a meeting on Sept 30,1980.

Dam Site	1st day	2nd day	3rd day	4th day	5th day
	Depths in mm				
Narmada Sagar	33.8 (28 Aug 1973)	100.6 (29 Aug 1973)	99.8 (30 Aug 1973)	90.2 (15 July 1944)	-
Sardar Sarovar	28.0 (28 Aug 1973)	63.0 (29 Aug 1973)	80.0 (30 Aug 1973)	61.0 (5 Sept 1970)	72.0 (6 Sept 1970)

8.2 Maximisation Factor for the Synthetic Storm (Studies Carried out by India Meteorological Department)

Moisture maximisation factor computed by India Meteorological Department using 35 years of dew point temperature data gave a factor varying between 1.3 and 1.4 (Table 6) and a uniform value of 1.35 for the synthetic storms was recommended for the entire catchment.

Table 6 - Maximisation factor with respect to highest dew point temperature and persistent dew point temperature during the storm period

	July	August	September
Betul	-	1.48	1.71
Jabalpur	1.35	1.25	1.26
Seoni	1.45	1.45	1.35
Baroda	1.25	1.35	1.17
Surat	1.35	1.45	1.35
Jalgaon	1.46	1.35	1.26
Nagpur	1.46	1.46	1.46
Khandwa	1.57	1.70	1.57

To study the maximisation factor variations, the second highest dew point on record was considered during the period of 35 years. The variability over various stations is shown in Table 7 for different monsoon months. It ranges from 1.07 to 1.46 with an average of 1.25.

Table 7 - Maximisation factor with respect to second highest dew point temperature and persistent dew point temperature during the storm period

	July	August	September
Betul	-	1.37	1.48
Jabalpur	1.17	1.09	1.07
Seoni	1.17	1.17	1.35
Baroda	1.08	1.17	1.05
Surat	1.25	1.17	1.17
Jalgaon	1.36	1.26	1.17
Nagpur	1.36	1.26	1.46
Khandwa	1.36	1.26	1.26

The maximum dew point series for the months of July, August and September were prepared for 8 individual stations in the catchment. The maximum values were picked up for the fortnights of storm occurrences in the catchment area. The return period analysis was done using two parameter Gumbel's distribution for extremes and applying maximum likelyhood technique for estimation of parameters. Considering a 100 year return period value of dew point, moisture maximisation factor ranging from 1.25 to 1.56 with an average value of 1.39 (Table 8) was obtained for the representative stations.

Table 8 - Maximisation factor with respect to return period values of dew point temperature and persistent dew point temperature during the storm period

	July			August			September		
	25yr	50yr	100yr	25yr	50yr	100yr	25yr	50yr	100yr.
Betul	-	-	-	1.55	1.66	1.76	1.61	1.75	1.93
Jabalpur	1.25	1.30	1.38	1.17	1.20	1.23	1.26	1.29	1.33
Seoni	1.35	1.45	1.54	1.35	1.45	1.56	1.47	1.61	1.68
Baroda	1.34	1.43	1.45	1.25	1.30	1.35	1.18	1.21	1.25
Surat	1.37	1.43	1.48	1.32	1.39	1.45	1.24	1.29	1.35
Jalgaon	1.57	1.69	1.80	1.24	1.27	1.32	1.26	1.30	1.35
Nagpur	1.47	1.57	1.62	1.31	1.36	1.38	1.31	1.36	1.41
Khandwa	1.50	1.57	1.69	1.38	1.43	1.47	1.83	2.13	2.37

Considering the highest dew point temperature and maximum dew point temperature during storm period, values ranging from 1.15 to 1.45 with an average of 1.32 were obtained for individual stations (Table 9).

Studies carried out by Central Water Commission indicated a value of 1.25 though not reported officially in the form of a report.

Table 9 - Maximisation factor with respect to highest dew point temperature and maximum dew point temperature during the storm period

	July	August	September
Betul	-	1.36	1.15
Jabalpur	1.15	1.15	1.16
Seoni	1.45	1.45	1.34
Baroda	1.24	1.24	1.07
Surat	1.24	1.45	1.35
Jalgaon	1.29	1.25	1.16
Nagpur	1.39	1.28	1.34
Khandwa	1.18	1.58	1.45

8.3 Summary of the Moving Storm Studies

In table 10, a summary of the inter-station lag, in other words, the time taken by a storm to move from one station to another is indicated for the four storms analysed. In view of the number of stations and their network varying from storm to storm, though it may be difficult to draw any conclusions readily it could be seen that the storm of Aug 1979, Aug 1978 and Sept 1970 are relatively fast moving storms as compared to the August 1973 storm. The storm of August 1978 was fast until it reached Bairagarh. During the recurving phase it became slow.

Table 10- Summary of lag time in hours at various self recording rain gauges in different storms

Station	3-6 Sept 1970	28- 31 Aug 1973	28-31 Aug 1978	7-10 Aug 1979
Pendra Road	0	0	-2 or -3	
Umaria		4	8	
Mandla	6	-1	0	1
Malanjkhand			1	2
Jamtara			5	1
Jabalapur	8	11	13	0
Lakhandon			6	
Narasimhapur			12	
Harai			7	4
Chindwara	14		7	
Bermanghat			7	9
Gadarwara			-	6
Pachmarhi	15	19	15	
Tawa			9	6
Bagratawa	15		9	6
Hoshangabad			9	
Barna Dam			17	10
Sarni Dam			15	
Betul	18	31	15	
Salwani			9	
Bairagarh	19	32	-	8
Punasa	29	40	-	
Mortakka			28	
Khandwa	32	41	18	
Mandleshar			-	27
Dharni	-	-	23	-
Thikri	33	48	24	
Burhanpur	-	-	25	
Barwani			25	
Indore	32	48	36	
Ujjain		49	-	
Khewadia colony	56		-	
Rajpipla			27	

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

(i) The conventional methods of depth-area-duration and depth-duration analysis do not yield critical depths for design purposes in Narmada catchment. Special technique to suit the meteorological, hydrological and topographical conditions of Narmada basin had to be tailored. A four day combined storm of 1973-1944 for Narmada Sagar and five day combined storm of 1973-1970 for Sardar Sarovar are considered appropriate.

(ii) Though doubts are expressed about the application of moisture maximisation for tropical regions, to account for the limitation of storm sample, the storms need to be maximised. In case of synthetic storms consisting of combination of the storms, different maximisation factors are to be used for the different constituent storms. However, India Meteorological Department has recommended a uniform maximisation factor of 1.35.

(iii) In view of the elongated shape of the basin and the time taken by storms for moving from upstream to down stream, the time distribution for each of the sub-catchment in the Narmada basin is to be evolved separately incorporating the necessary lag from upstream to downstream while keeping a critical sequence of rainfall blocks in each of the sub-catchment. Using different groups of S R rain gauges from out of 11 SRRG stations, IMD has recommended different time distributions for four main sub-catchments.

(iv) The inter-station distance and inter-station correlation were not well related so as to indicate the expected decrease in correlation coefficient with increasing distance, due to sparse SRRG network in Narmada basin.

(v) The analysis of small sample of four storms used in studying of the moving storms indicated a fairly consistent movement and speed of movement of storms over Narmada basin.

9.2 Recommendations

Though significant improvement has been achieved through sequential maximisation of storm, the methods used for moisture maximisation and time distribution fail to take into account the movement of the storm over the catchment and its effect on the flood hydrographs in each sub-catchment and on the main river. Also, the data sample used for determining the time distribution is small. The moving storm studies summarised in this report are some preliminary steps in this direction. More data and further studies on modelling the movement of storms and their speeds are necessary for studying their effect on flood flows.

Though, part of the catchment is orographic, no attempt has been made to separate the orographic and non-orographic parts for design storm estimation due to non availability of upper air meteorological data. Applying a uniform maximisation factor throughout the basin is unrealistic in view of the elongated catchment and typical orography. Storm modelling for the orographic areas needs to be studied as recommended in WMO Operational Hydrology Report No.1 and other studies in USA.

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